Acoustic Emission for Non-Destructive Testing of Bridges and other Transportation Infrastructure*

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1. INTRODUCTION

Highway brides are crucial components of a healthy and productive transportation infrastructure. There is an ever increasing demand for ensuring the integrity and performance of our nation's bridges. A variety of factors may lead to their degradation. Cracks and flaws in steel bridge structure components may have originated during the fabrication process and grow from there due to traffic fatigue or corrosion or both. Load, environment and corrosion loss affect the performance and cause deterioration. Concrete bridges in long-term service suffer from degradation caused by corrosion of reinforcement that is believed to have origin at the concrete - reinforcement interface. The main cause of deterioration of highway bridge structural components is a complex combination of factors that include load and environment. Such factors damage the bridges through processes such as development of cracks, their growth, bridge structural member plastic/elastic deformations and active corrosion. This complex combination of degradation factors introduces an undermined and unpredictable degradation rate factor. At the last TRB meeting held in Washington, DC, diffusion of chlorides, oxides and such radicals into the structural components was reported by a number of researchers to be the primary cause for corrosion. Cracking of concrete related and unrelated with corrosion is also a major problem. The bridges that are usually subjected to severe environmental effects require timely inspection and evaluation of their structural health. Unpredictability of the degradation process introduces a degree of uncertainty in the decision making process regarding the frequency of inspection, planning for repair and replacement of the affected structural parts. Since there is physical limitation on access to various components of a bridge structure, any visit for inspection becomes expensive even if the task is to inspect only a single structural element. The consequences of a bridge failure due to uncertainty in predicting degradation could be disastrous to the motorist and catastrophic to the nation's economy.

2. NATIONS BRIDGES: STATUS REPORT

According to the Federal Highway Administration created National Bridge Inventory database as part of the National Bridge Inspection Program, in 1992 there were 199,090 (46%) of the nation's bridges (including in Puerto Rico) that were rated as structurally deficient or functionally obsolete. Because of structurally deficient ratings, the bridges were either closed or restricted to light vehicles. Bridges rated as functionally obsolete were those that had older design features and though not unsafe for vehicles, could not safely accommodate current volume, sizes or weights of traffic. As of December 2004, there were only 158,318 bridges with the same rating, a decrease of 20.5%. Part of this decrease can be contributed to the funding provided by the Transportation Equity Act for the 21st Century (TEA-21). The law authorized $218 billion for highway and transit construction programs through 2003, thus increasing federal funding for transportation programs by 40 percent over previously authorized levels. Later the FHWA released report FHWA-RD-01-156 titled "Corrosion Costs and Preventative Strategies in the United States" which was initiated by the NACE International – The Corrosion Society and mandated by congress as part of TEA-21. This 2-year study reviewed the direct costs associated with metallic corrosion. The report covered 5 major sector categories broken into 26 sectors. According to this study, it is estimated that $8.3 billion is spent on highway bridges, including $3.8 billion to replace deficient bridges over the next 10 years, $2 billion on maintenance and capital costs of concrete decks and $2 billion for concrete substructures. This part of the study also estimated the indirect cost to the user would be as high as 10 times that of the direct corrosion cost due to traffic delays and lost productivity.

While the percentage of deficient and obsolete bridges has decreased, despite the rising costs of maintenance, the ASCE 2003 Progress Report clarifies that current funding trends of state DOT’s could hamper progress on addressing future bridge deficiencies and once again, federal action will be needed to prevent deterioration. In the face of funding shortfalls, states and owners are now beginning to look at technology for alternative use materials for bridge replacement, repair and rehabilitation.

TEA-21 and the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 were to give states the necessary funding and the flexibility to attempt new transportation solutions without requiring full replacement. However, this action initiated at the federal level lacks uniformity of implementation at the state level resulting in funding gaps for needed maintenance programs. Though the TEA-21 law expired on September 30, 2003, it was extended several times. It was not until August 10, 2005, nearly two years after TEA-21 expired, that the President signed SAFETEA-LU into law now providing $286.4 billion over 6 years for highway and transit construction and maintenance. However, it will still be a few years before it can be determined how well this new funding meets the needed funding goals of each state in order to adequately meet their maintenance goals.

3. RESPONSE OF STRUCTURES UNDER STRESS

Structures under stress produce sound that a human ear may not always be able to hear. The phenomenon of acoustic sound generation in structures under stress is called acoustic emission (AE). Acoustic emission is basically the generation and propagation of stress waves in materials due to effects of stress such as deformation, initiation and growth of a crack, opening and closing of a crack, diffusion and movement of a dislocation, twining and phase transformation, breakage and de-lamination in composite materials etc. The sources of AE are predominantly damage-related. A careful AE monitoring leads an investigator to the prediction of material failure. Over the past decades, various acoustic emission monitoring devices have been developed for nondestructive testing and evaluation of structures including related with transportation infrastructure.

There are many non-destructive evaluation methods which can locate a crack but not all such methods are capable of locating and characterizing a dynamic (growing/active) crack that is most likely to result in structure failure. However, a scientifically sound, technically feasible, reasonably predictable and economically attractive bridge management program needs to be developed for efficient functioning of the bridge and the bridge engineer. Non-Destructive Testing (NDT) technique of Acoustic Emission (AE) has the potential to eliminate much of the subjectivity in traditional methods of manual (visual) inspection and bridge condition determination. AE testing is capable of performing the critical tasks of detection, location and determination of the dynamics of flaws that are likely to cause serious impairment of the bridge structure and its ability to perform as designed. A critical advantage of AE testing over its other NDT counterparts is its ability to respond only to active flaws making it a principal candidate for flaw characterization and real time health monitoring of highway bridges.

4. AE, ITS DETECTION AND USE IN MEASUREMENT OF CRACK GROWTH DURING FATIGUE

Acoustic emissions are generated during the process of defect origination such as crack growth, crack propagation and even during plastic deformation of the material in a highly stressed zone adjacent to the tip of the crack. The NDT technique of Acoustic emission (AE) is based on the principle that each flaw is associated with varying types and levels of deformations that release energy in the form of stress waves whenever a dynamic micro-structural damage such as crack growth occurs. Each deformation become sources of AE and generates signals characteristics of the source. Sudden release of energy from a localized dynamic source such as crack extension in a stressed material generates elastic stress waves that propagate creating AE signals that can be detected by remote sensors. Basic principles involved in measurement of AE are the changes in propagation parameters of a wave signal through a medium. These changes in signals are amplified with the help of resonant piezoelectric devices. The amplified signal looks different in resemblance to the emitted signal. By measuring the signal parameters such as counts, amplitude, duration, rise time and counts energy (the area under the rectified signal envelope), a multitude of quantitative information on the magnitude of material defects, location and time of their origination, and the rate of their propagation can be obtained. These signal related parameters and the hit description that includes the external parameters such as the current value of the applied load, the time of detection, the cycle count during the fatigue and the level of continuous background noise at the time of detection are fed to a computer for analysis.

5. AE APPLICATION TO STEEL BRIDGE STRUCTURES: A BRIEF REVIEW

Pollock and Smith (1971), perhaps the first to apply AE for testing bridges, collected data during proof testing of a portable tank bridge for the British Ministry of Defense. They demonstrated that signals recorded in the field could be associated with test results on laboratory specimens. In 1972 Argonne National Laboratory proposed to monitor emissions from a bridge on I-80 in Illinois and Hopwood (1973) monitored emissions from the eye-bar members of a bridge. Although good transmission through eye-bar members of the bridge was observed, signal to noise ratio remained a serious problem. An extensive program funded by the Federal Highway Administration (FHWA) with Battelle Pacific Northwest in the late 1970s resulted in the development of a battery powered digital acoustic emission monitor (Hutton and Skorpik, 1975 and 1978) that allowed periodic data recording and storage on erasable programmable read only memory chips for further processing and evaluation. This study was the first time demonstration of the potential of AE frequency spectrum analysis for centralized signal processing. The noise to signal ratio, however, remained a concern during these studies as well.

Kentucky Transportation Research Center, during 1980 – 82, used the digital AE monitor to periodically monitor a bridge on I-471 and reported effects of traffic and rainfall as sources of emission noise (Miller, 1987).

Dunegan Corporation, under contract from the West Virginia Department of Highways, examined the practical difficulties in long term AE monitoring of bridges (Hartman, 1983). The financial benefits of AE monitoring over the use of periodic ultrasonic, magnetic particle, or liquid penetrant inspections of known defects were discussed. United Technologies Research Center, under contract from FHWA, performed laboratory and field tests to characterize AE signals from flaws and various noise related sources (Miller et al., 1983). Both time and frequency domain representations of signals were investigated. Pattern recognition and source classification for filtering out noise and for discriminating between different damage related events, such as brittle fracture and fatigue, were demonstrated. These studies were facilitated by development of a field worthy AE sensor capable of detecting a broad band of frequencies was developed during the course of the program.

Prine and Hopwood (1985) considered an acoustic emission weld monitoring system for both fabrication and in service evaluations of bridge components. They pointed out that emission signals from bridges contain information on traffic volume and vehicle speed and weight, as well as on structural details and transducer characteristics.

In 1987, University of Maryland monitored the Woodrow Wilson Bridge on the border of Maryland and Virginia for the Maryland Department of Transportation. They found that the predominant peak frequency of noise emissions is distinctly lower than crack related emissions. Suitable software filters, designed to exclude signals whose time domain parameters do not fall within the range of parameters of crack related emissions, can eliminate most noise signals (Vannoy et al., 1987). These studies were followed by extensive laboratory tests on full size A588 bridge beams (Vannoy and Azmi, 1991). AE parameters of cracks versus noise on rolled, welded, and cover plated beams were characterized in both time and frequency domains. It was also determined during these studies that corrosion has no effect on the time domain parameters of emissions from cracks. A related study at the University of Maryland (Hariri, 1990) sought to develop a database of signal characteristics from different bridge steels and various material and loading conditions, as well as from different part geometries and thicknesses for application on bridge structure AE. This study showed that noise filters, dictated by the type of material, thickness, paint layer, and corrosion conditions of a monitored part, can be developed using ranges of AE parameters provided by such a database. Interestingly, the AE signal attenuation due to a layer of surface paint was found to be insignificant.

FHWA has conducted a series of field tests on several bridges. Results of these tests have emphasized the need for source location and guard sensors for filtering out irrelevant acoustic emissions events (Carlyle, 1993; Carlyle and Ely, 1992; Carlyle and Leaird, 1992). AE was demonstrated for testing the effectiveness of retrofits as well as in finding new cracks.

Canadian National Railways sponsored AE monitoring on 36 railroad bridges over a period of three years (Gong et al., 1992). Using a known functional relationship between the emission count rate and the stress intensity factor range, this study was able to classify cracks into five levels of severity. Spatial discrimination and filtering using parameter windows determined from laboratory tests on bridge steels were used to eliminate noise.

Effectiveness of combining AE and strain gage monitoring was demonstrated on three bridges in Wisconsin and California (Prine, 1993). In a departure from the usual crack characterization function of AE monitoring, a bascule bridge was tested to determine the cause of loud impact noises that accompanied the lifting and lowering of the bridge. Continuous AE was used in enhanced fatigue crack detection in aging aircraft by McBride et al. (1993). AE has also been used in detecting the onset of crack growth in rail steels (Bassim et al., 1994). Such data has been used in attempts to design theoretical models for fatigue damage mechanisms (e.g. Fang et al., 1995). AE has been used in United Kingdom to investigate integrity of welded steel structures (Roberts et al., 1999). These studies have led to correlate the propagation of cracks in steel, welded steel compact tension and T-section girder test specimens with rates of AE (Roberts et al., 2003).

Overall, the research to date has provided a reasonable scientific base upon which to build an engineering application of AE as part of a bridge management program. In addition, continued advances in electronics, such as faster microprocessors, provide testing capabilities that were not possible even a few years ago. To a nondestructive evaluation method that relies heavily on instrumentation, these advances give extra encouragement that better results will be obtained through further studies.

Nearly all of the work to date has sought to use AE to detect the initiation of damage, locate it, and then monitor its growth and severity of the damage. The approach taken in this work limits the application to that of monitoring. From an engineering point of view this restriction is quite significant. The limit means that the size and complexity of the AE system required may be greatly reduced. Noise sources associated with the structure may be eliminated, since the location of the test source (the problem area) is known. Requirements of monitoring, to support decision making of the bridge engineer, make it possible to configure a system that provides constant surveillance and early warning of changes in the condition of a critical bridge component.

Hampton University, Hampton, VA and the Virginia Transportation Research Council (VTRC), Charlottesville, VA are working on a new study to monitor the stay cables of a major bridge on Interstate 295 over the James River along the I-95 corridor (Fig. 1).

Fig. 1: Varina-Enon Bridge on I-295 near Richmond, VA (Courtesy VDOT/VTRC)

This study is on the short-term evaluation of VDOT owned Varina-Enon bridge cables using AE sensors to determine:

-if a bridge cable wire broke, (friction) will cause AE to be generated when broke.
-if corrosion is taking place in the area close to sensor, AE sensors will hear it.
-if micro cracking is taking place in the test element, AE will sense it.
-if the AE could be used as inspection tool for VDOT

The bridge's supporting cables contain steel strands with individual wires. This study aims to determine if the condition of the strands can be assessed by short-term monitoring with acoustic-emission (AE) instrumentation on a single stay cable of the Varina-Enon Bridge during periods of both low traffic volumes (acoustically quiet) and high traffic volumes (acoustically noisy). AE monitoring has been conducted during summer and winter temperature extremes involving high- and low-traffic volumes. The aim of this study is also to evaluate signature sounds and/or wire breaks that may have occurred during the test periods.

The purpose of this study is also to enhance VDOT's ability to evaluate the health of this structure and to pinpoint regions that might require more in-depth inspections. It is all part of the overall effort to ensure the continued integrity of the nation's bridges.

To perform this study, acoustic emission sensors have been strategically affixed to a single cable and monitored for two and a half months each during the winter and the summer months of 2008 and 2009. AE Sensor Highway II™ designed by Physical Acoustics Corporation (PAC) and Mistra's Group to:

- Monitor the effectiveness of repairs/retrofits
- Determine if pre-existing/known defects are active
- Monitor "hidden areas" where visual inspection is difficult
- Detrmine if high stress areas show flaw like activity

has been used for data acquisition.

6. AE SENSOR INSTALLATION

Sixteen AE Sensors and their control system (Sensor Highway II™ (SH II™) DAQ system) manufactured by Physical Acoustic Corporation have been installed across the entire span of the cable attached to the north pylon including in the areas inside the pylon (please see Figures 2, 3 and 4).

FIG. 2: SENSOR INSTALLATION

FIG. 3: SENSOR INSTALLATION

FIG. 4: SENSOR HIGHWAY II DAQ SYSTEM INSTALLED NEAR THE NORTH PYLON

Sensors 1, 2, 3 and 4 are installed on the north span of the cable outside the pylon, 13, 14, 15 and 16 on the south span of the cable outside the pylon, and 5, 6, 7, 8, 9, 10, 11, 12 on the part of the cable located inside the pylon. A broadband wireless connection to the sensor highway II™ DAQ system has been used for remote access to the data from SH – II™. The data is being analyzed using AE Win software. A sample plot of the data representing AE events (hits), their amplitude and the date and times recorded recently on August 12, 2008 is shown in Figure 5.

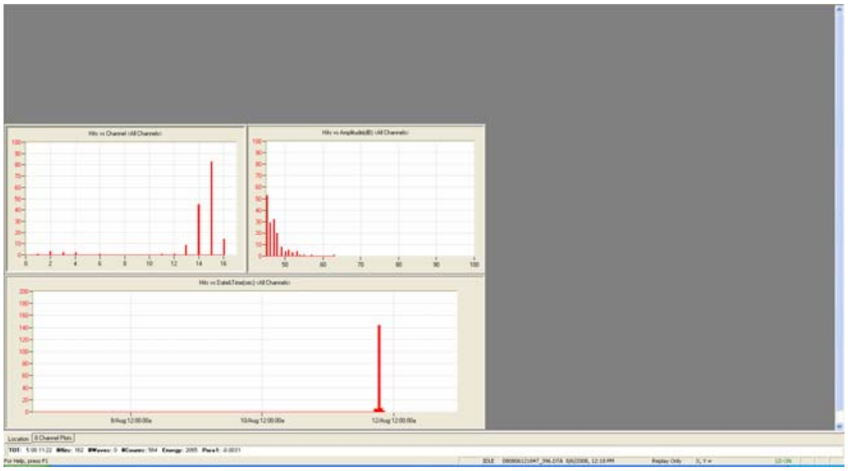

Figure 5: A sample plot of recorded AE data by installed sensors

7. RESULTS

Some of the significant features of the data in Fig. 5 are:

1. The number of AE hits and their amplitudes are extremely low indicating absence of any damage during the test period.
2. Only a few of the sensors located on the cable outside of the pylon (sensor 1, 4 15 and 16) have recorded some hits indicating that the response is due to extraneous factors such as rain and/or wind.
3. The sensors (15, 16) located towards south of the pylon have recorded more hits than on towards north (1 and 4) confirming the directional effects of the falling rain.
4. There is absolutely no hits recorded by sensors (5, 6, 7, 8, 9, 10, 11 and 12) located inside of the pylon confirming that the recorded hits are weather related.

A plot of two acquisitions of AE data on a rainy day (August 12, 2008) is plotted in Fig. 6. Recording of the AE hits only by the sensors located out side the pylon is remarkable. This clearly confirms the fact that the AE response is related to weather and not due to any damage to the cable. The data also indicates an extremely light intensity rain.

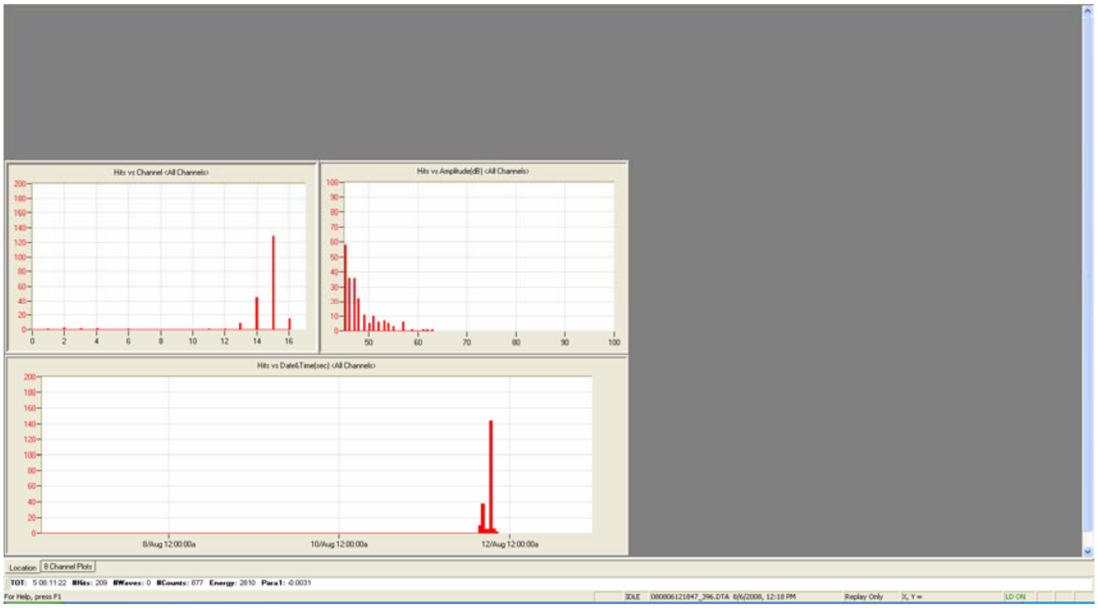

Fig. 6: Combined AE data plot for two acquisitions on a rainy day.

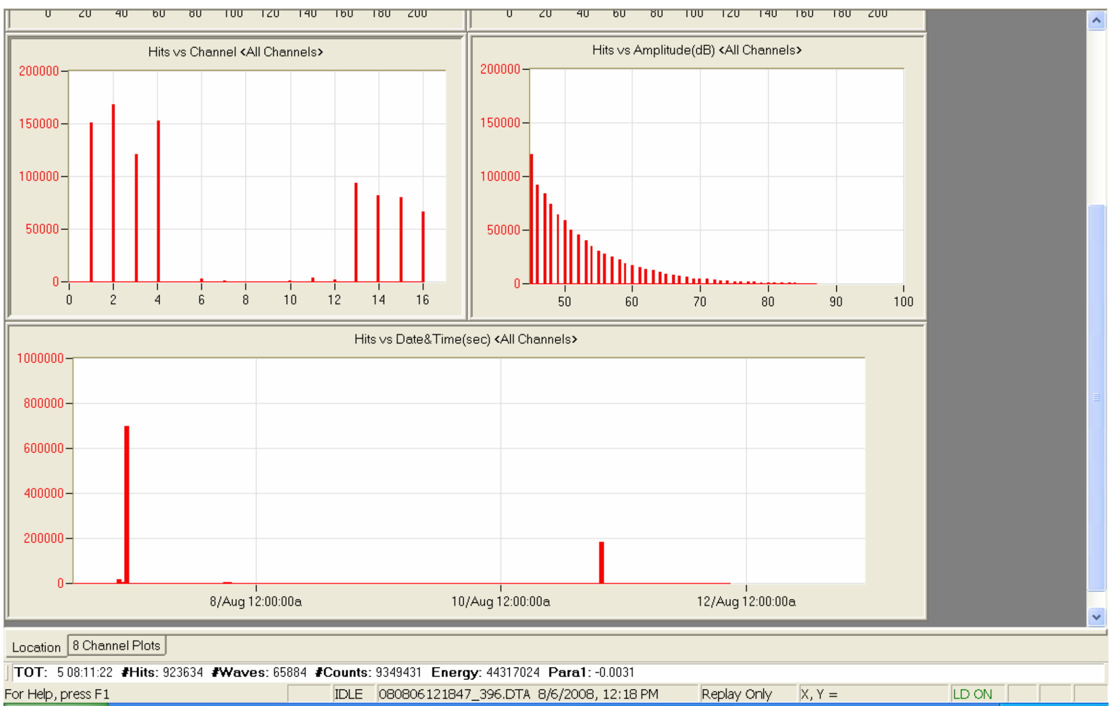

Fig. 7: Plot of the acquired data during August 6 – 12, 2008.

A plot of the data acquired during August 6 – 12, 2008 is shown in Fig. 7. It is remarkable to note absence of any AE activity between the two rainy days of August 6 and August 11, the rain fall being higher on August 6-7 than on August 11-12. The directional effects of rain fall on the cable, being more intense from south are also clear. Absence of AE activity during these two events is an indication of sound health of the test cable. The plot of the data recorded between August 6 -12, 2008, shown in Fig. 7 indicates the bridge being hit by heavy rain and perhaps also a storm on August 7 – 9, 2008.

The location of the source of AE activity in relation to the location of the sensors is best described in the plots of Fig. 8 where Fig. 8(a) depicts locations of sensors 1 – 4 installed on the north span with respect to the pylon and Fig. 8(b) depicts locations of sensors 13 – 16 installed on the south span of the test cable with respect to the pylon. There is more AE activity originating 1-4 than between 13-16. This fact is clearly demonstrated in Fig. 8(c). Fig. 8(d) shows the distribution of amplitude of the AE emissions.

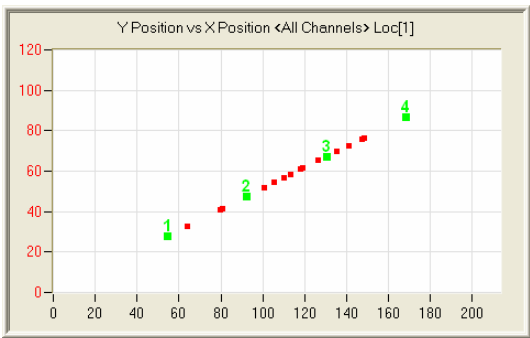

Fig. 8(a): AE Sensor locations on North Span of the cable

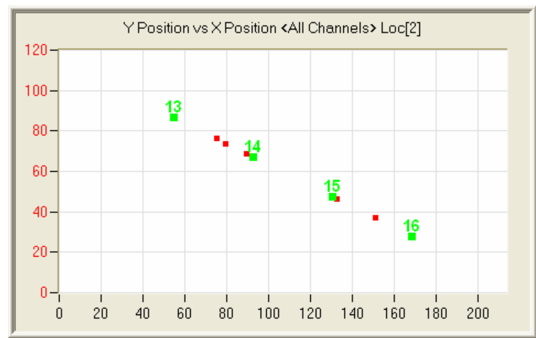

Fig. 8(b): AE Sensor locations on south Span of the cable

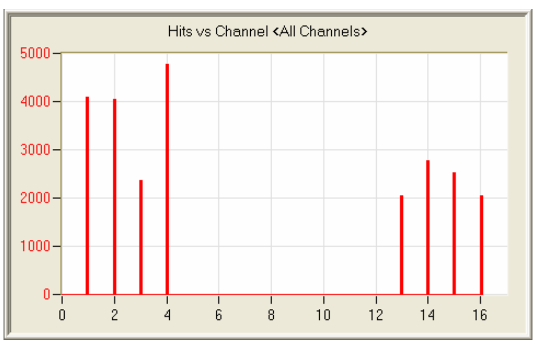

Fig 8(c): AE hits on recorded by sensors

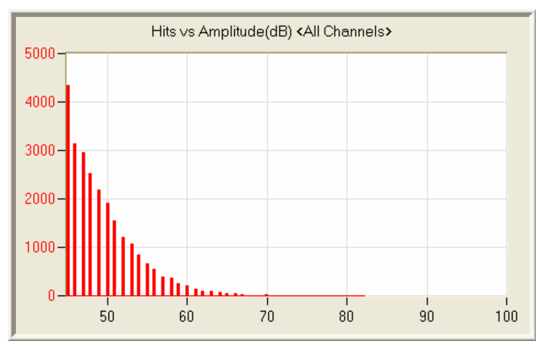

Fig 8(d): AE hits and their amplitudes

8. CONCLUSIONS

1. AE technique is capable of hearing even feeble sounds originating from impacts on the bridge cable.
2. The preliminary AE recordings thus far indicate that the cable #10 under investigation is in sound health.
3. The AE data can be monitored, recorded and analyzed on a real time basis from a remote location such as from the office of the bridge engineer/inspector.
4. AE is capable of identifying factors related to the health of the bridge cable and factors such as weather unrelated to the health of the bridge cable.

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